Colour dipole approach to Drell-Yan and heavy quarkonia production at RHIC and LHC

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Outline

1. Motivation
2. Color Dipole Description of Drell-Yan process
   - $pp \to \gamma^*/Z^0 \to \ell^+\ell^-$
   - $pA \to \gamma^*/Z^0 \to \ell^+\ell^-$
   - Dilepton - hadron correlations
3. Color Dipole Description of Quarkonium Production
4. Conclusions and Outlook

Introduction

Drell-Yan and heavy quarkonia studies

- Drell-Yan (DY) in $pp/pA/AA$ collisions is an excellent tool to investigate QCD in an extended kinematical range of energies and rapidities.
- DY in *pp*@LHC allows to test the Standard Model (SM) and search for New Physics beyond the SM. In pA/AA at RHIC and LHC it could be used to investigate the onset of initial-state effects.
- Color dipole description of DY in pp/pA allows to test different dipole cross section parametrizations used in low-x DIS.
- Quarkonia production in pp/pA, as well as high-p_T forward particle production in pA, are traditionally very important probes of QCD dynamics e.g. QCD factorisation, gluon resummation, higher order PT and non-PT effects, medium properties, CGC etc.
- In pp heavy quark masses provide hard scale to study quarkonia production mechanisms in pQCD (factorisation breaking, CS vs. CO,...) $c\bar{c}$ are special - m_c is at the boundary between pQCD and soft QCD.

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Frame-dependent description of Drell-Yan process

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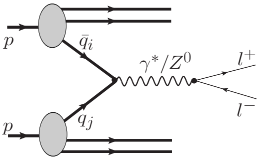

- In the target rest frame, the DY process looks like fragmentation of a projectile quark into a dilepton via bremsstrahlung of a heavy photon

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- The photon can be radiated before or after the quark scattering.

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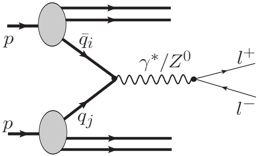

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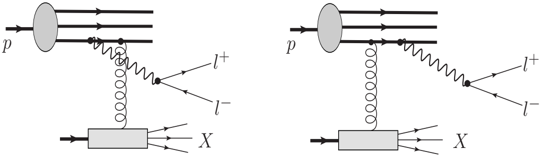

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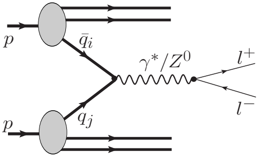

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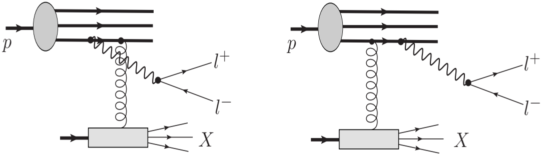

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Color dipole description of DY process

J. Raufeisen *et al.*, Phys. Rev. D **66**, 034024 (2002):

- *In the kinematical region where $\sqrt{s} \gg$ all other scales (e.g. m_c, m_b), the DY process can be formulated in the target rest frame in terms of the same color dipole cross section which is used in low-x DIS [1]:*

$$\boxed{\frac{d\sigma(qN \to \gamma^* X)}{d\ln\alpha} = \int d^2\rho\, |\Psi_{\gamma^* q}(\alpha,\rho)|^2\, \sigma^N_{q\bar{q}}(\alpha\rho, x)}$$

$\Psi_{\gamma^* q}(\alpha,\rho)$ – LC wave function; gives rate of $q \to \gamma^* q$ EM radiation, is PT calculable.
$\sigma^N_{q\bar{q}}$ – dipole cross section; has NP origin, comes from phenomenology (GBW [2] *etc.*)
α – LC momentum fraction of parent quark taken away by γ^*.
ρ – transverse separation between γ^* and final quark.

$$\frac{d^2\sigma(pN \to \ell^+\ell^- X)}{dM^2 dx_F} = \frac{\alpha_{em}}{3\pi M^2}\frac{x_1}{x_1+x_2}\int_{x_1}^{1}\frac{d\alpha}{\alpha^2}\sum_{f=1}^{N_f} Z_f^2 \left[q_f\left(\frac{x_1}{\alpha},\mu^2\right) + \bar{q}_f\left(\frac{x_1}{\alpha},\mu^2\right)\right]\frac{d\sigma(qN \to \gamma^* X)}{d\ln\alpha\, d^2p_T}$$

$x_1 = \frac{2\,P_2\cdot p}{s}$, $x_2 = \frac{2\,P_1\cdot p}{s}$, $s = (P_1+P_2)^2$, $p^2 = M^2 \equiv M^2_{\ell\bar{\ell}}$, $x_F = x_1 - x_2 = 2\,p_L/\sqrt{s}$
$\mu_F^2 = p_T^2 + (1-x_1)M^2$ – factorization scale at which the projectile PDF q_f is probed.

[1] N. N. Nikolaev and B. G. Zakharov, Z. Phys. C49, 607 (1991)
[2] K. Golec-Biernat and M. Wüsthoff, Phys. Rev. D 59, 014017 (1999); *ibid* 60, 114023 (1999); PRL 86, 596 (2001)

$pp \to \gamma^*/Z^0 \to \ell^+\ell^-$: Color dipole approach @ large M

- Quark bremsstrahlung of a virtual gauge boson G^* ($G = \gamma, Z^0$)

$$\frac{d\sigma(pp \to [G^* \to \ell^+\ell^-]X)}{d^2p_T dM^2 d\eta} = \mathcal{F}_G(M)\,\frac{d\sigma(pp \to G^* X)}{d^2p_T d\eta}\,, \qquad G = \gamma^*/Z^0$$

where $\mathcal{F}_\gamma(M) = \frac{\alpha_{em}}{3\pi M^2}\,, \qquad \mathcal{F}_Z(M) = \mathrm{Br}(Z^0 \to \ell^+\ell^-)\rho_Z(M)$

and $\rho_Z(M) = \frac{1}{\pi}\,\frac{M\Gamma_Z(M)}{(M^2 - m_Z^2)^2 + [M\Gamma_Z(M)]^2}\,, \qquad \Gamma_Z(M)/M \ll 1\,,$

with $\Gamma_Z(M) = \frac{\alpha_{em} M}{6\sin^2 2\theta_W}\left(\frac{160}{3}\sin^4\theta_W - 40\sin^2\theta_W + 21\right).$

- Calculations done with m_u=m_d=m_s=0.14GeV, m_c=1.4 GeV, m_b=4.5 GeV, and with the CT10 NLO parametrization* of the projectile quark PDFs and the factorization scale $\mu_F = M$.

*) H. L. Lai *et al.*, Phys. Rev. D **82**, 074024 (2010).

Color dipole cross section parametrizations used

- Dipole cross section parametrizations used: GBW, BGBK, IP-sat.

GBW: K. Golec-Biernat and M. Wüsthoff, Phys. Rev. D **59**, 014017 (1999); 60, 114023 (1999); PRL **86**, 596 (2001)

$$\sigma_{q\bar{q}}(\rho, x) = \sigma_0 \left[1 - \exp(-\frac{\rho^2 Q_s^2(x)}{4})\right], \; Q_s^2(x) = Q_0^2 \left(\frac{x_0}{x}\right)^\lambda$$

BGBK: J. Bartels, K. Golec-Biernat and H. Kowalski, Phys. Rev. D **66**, 014001 (2002)

$$\sigma_{q\bar{q}}(\rho, x) = \sigma_0 \left[1 - \exp\left(-\frac{\pi^2}{\sigma_0 N_c}\rho^2 \alpha_s(\mu^2) x g(x, \mu^2)\right)\right], \; \frac{\partial x g(x,\mu^2)}{\partial \ln \mu^2} = \frac{\alpha_s(\mu^2)}{2\pi} \int_x^1 dz P_{gg}(z) \frac{x}{z} g(\frac{x}{z}, \mu^2)$$

IP-sat: H. Kowalski, L. Motyka and G. Watt, Phys. Rev. D **74**, 074016 (2006); G. Watt and H. Kowalski, ibid D **78**, 014016 (2008)

$$\sigma_{q\bar{q}}(\rho, x) = 2 \int d^2 b \left[1 - \exp\left(-\frac{\pi^2}{2N_c}\rho^2 \alpha_s(\mu^2) x g(x, \mu^2) T_G(\mathbf{b})\right)\right], \; T_G(\mathbf{b}) = (1/2\pi B_G) \exp(-b^2/2B_G)$$

- $\sigma(pp \to Z^0)$ is sensitive to dipole cross section parametrizations:

$\sqrt{s}$ (TeV)	GBW	BGBK	IP-SAT	DATA [nb]
7	0.950	1.208	0.986	0.937 ± 0.037 [1] 0.974 ± 0.044 [2]
8	1.083	1.427	1.183	1.15 ± 0.37 [3]
14 (13)	1.852	2.797	2.514	(1.98 ± 0.39) [4]

[1] ATLAS: G. Aad *et al.* (ATLAS Collaboration), JHEP **12**, 060 (2010).
[2] CMS: V. Khachatryan *et al*. (CMS Collaboration), JHEP **10**, 132 (2011).
[3] CMS: V. Khachatryan *et al*. (CMS Collaboration), Phys. Rev. Lett. **112**, 191802 (2014).
[4] ATLAS: G. Aad *et al.* (ATLAS Collaboration), Phys. Lett. B **759**, 601 (2016).

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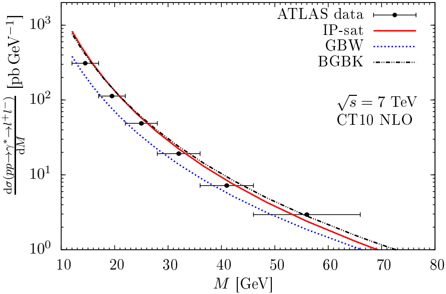
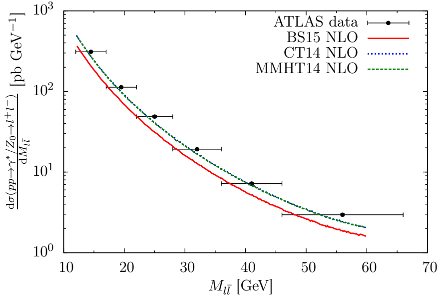
DY: Color dipole approach vs. NLO pQCD calculations

Phys. Rev. D **93**, 034023 (2016)



Nucl. Phys. A **948**, 63 (2016)



BS15: C. Bourrely and J. Soffer, Nucl. Phys. A **941**, 307 (2015)
CT14: S. Dulat *et al.*, arXiv:1506.07443v2 [hep-ph]
MMHT14: L. A. Harland-Lang *et al.*, Eur. Phys. J. **75** 5, 204 (2015)

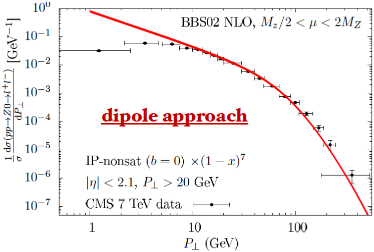
ATLAS data: G. Aad *et al.*, JHEP **1406**, 112 (2014)

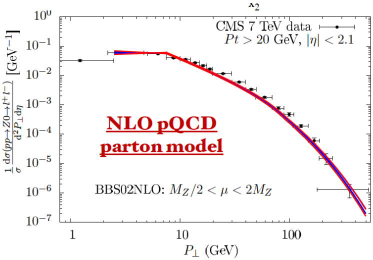
- Confirms previous observation[1,2] that dipole approach effectively accounts for higher order pQCD corrections

[1] J. Raufeisen, J.-C. Peng and G. C. Nayak, Phys. Rev. D **66**, 034024 (2002);
[2] M. B. Johnson *et al.* Phys. Rev. C **75**, 035206 (2007); M. B. Johnson *et al.* ibid C **75**, 064905 (2007).

DY: Color dipole approach vs. NLO pQCD calculations

- CMS data on $pp \to Z^0 \to \ell^+\ell^-$





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- Fails outside the region of dipole description validity (*i.e.* at low p_T).

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$pp \to \gamma^*/Z^0 \to \ell^+\ell^-$ @ LHC

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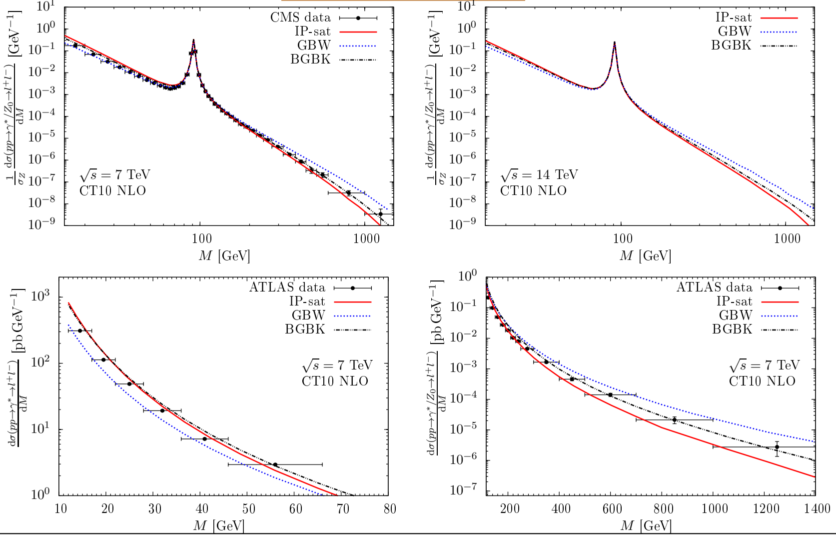

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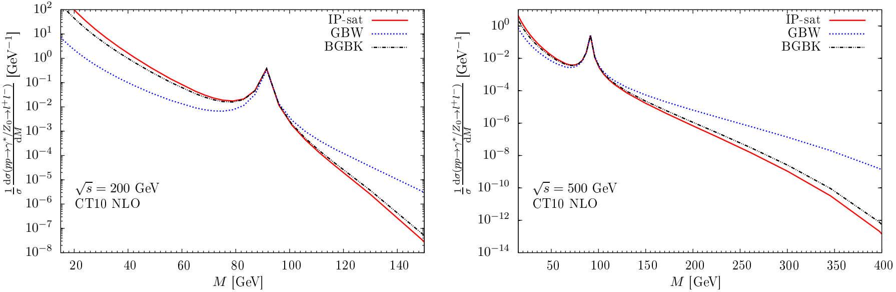
CMS: V. Khachatryan *et al*. (CMS Collaboration), Eur. Phys. J. **75**, 147 (2015).

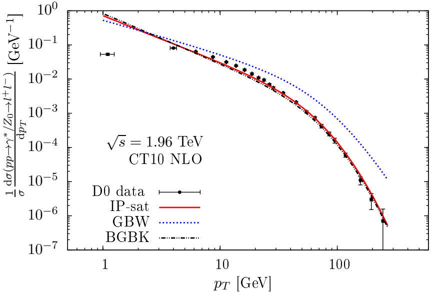
$pp \to \gamma^*/Z^0 \to \ell^+\ell^-$ at large M @ RHIC

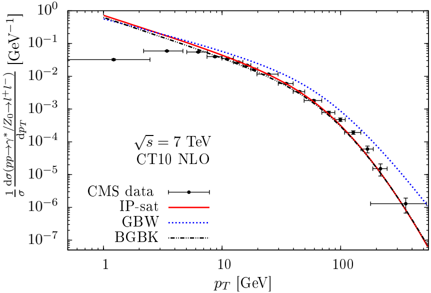
Phys. Rev. D **93**, 034023 (2016)

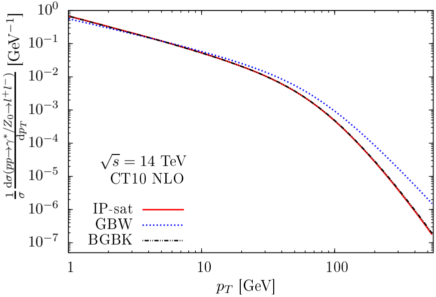


- Dilepton invariant mass spectra at large M are sensitive to different dipole cross section $\sigma^N_{q\bar{q}}$ parametrizations.

DY: Color dipole approach @ Tevatron and LHC







Phys. Rev. D **93**, 034023 (2016)

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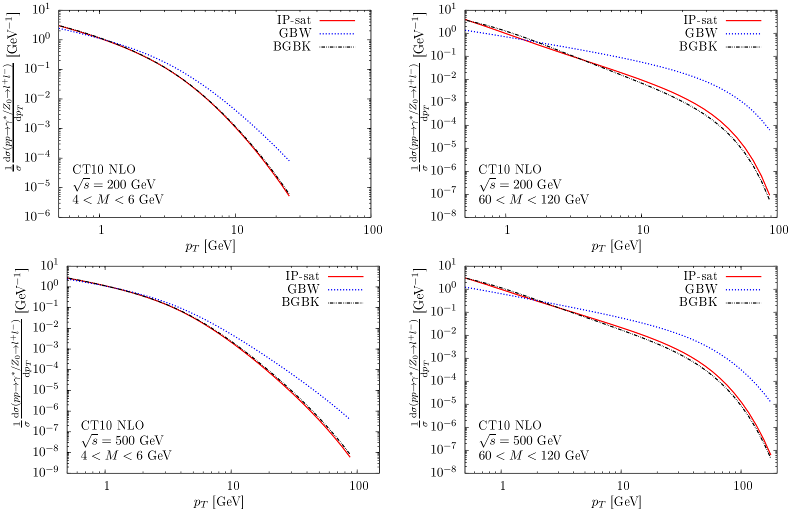
D0: V. Abazov *et al.*, Phys. Rev. D 76, 012003 (2007).
CMS: S. Chatrchyan *et al.*, Phys. Rev. D 85, 032002 (2012).

Color dipole predictions for DY@RHIC

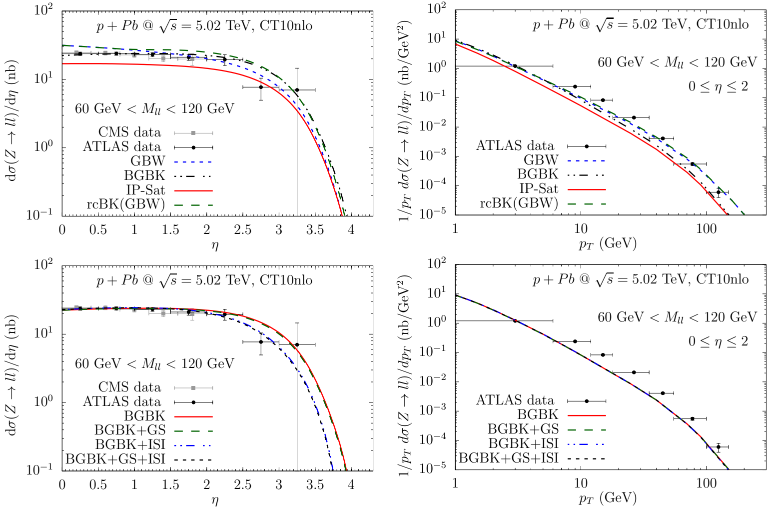
Phys. Rev. D **93**, 034023 (2016)



- Sensitive to different parametrizations of dipole cross section $\sigma^{N}_{q\bar{q}}$

Color dipole approach @ LHC: $pPb \to \gamma^*/Z^0 \to \ell\bar{\ell}$

Phys. Rev. D **93**, 094027 (2016)



ATLAS: G. Aad *et al.* (ATLAS Collaboration), Phys. Rev. C**92**, 044915 (2015).

CMS: V. Khachatryan *et al*. (CMS Collaboration), arXiv:1512.06461 [hep-ex].

Dilepton - hadron correlations

- In both pA and pp collisions DY production is accompanied by hadron production from fragments of the quark which radiated γ^*.

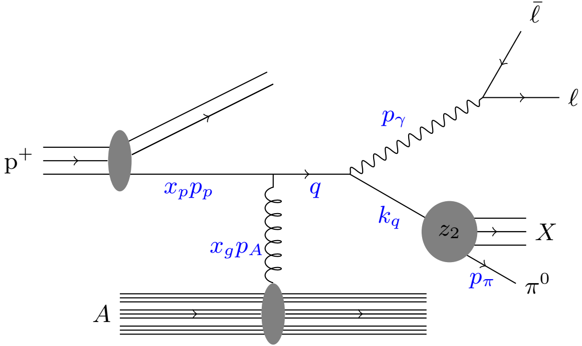


Figure from A. Staśto *et al.*, Phys. Rev. D **86**, 014009 (2012).

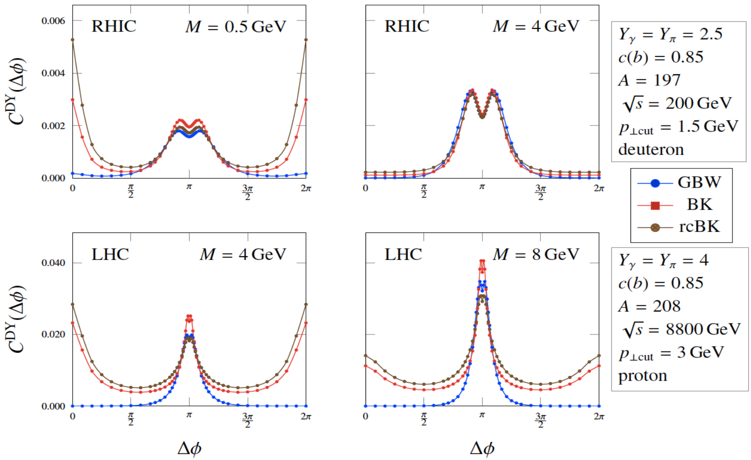
$\Rightarrow$ Study γ^*-h azimuthal correlations*

$\star$) For γ-h correlations see: A. H. Rezaeian, Phys. Rev. D **86**, 094016 (2012),

J. Jalilian-Marian and A. H. Rezaeian, Phys. Rev. D **86**, 034016 (2012).

γ^*-π azimuthal correlations in pA

A. Staśto *et al.*, Nucl. Phys. A **904-905**, 837c (2013)



In pA dipole gluon distribution at small-x as well as the cross section vanish for $p_T^g \to 0$

$\Rightarrow$ quark, in order to radiate photon, acquires its p_T via multiple scattering with gluons instead

$\Rightarrow$ double peak structure on the away side $\Delta\phi = \pi$ appears

[A. Staśto *et al.*, Phys. Rev. D **86**, 014009 (2012)].

G^*-h azimuthal correlation function $C(\Delta\phi)$

- Azimuthal correlations between dilepton and hadron are investigated using coincidence probability per trigger particle G^*:

$$\boxed{C(\Delta\phi) = \frac{2\pi \displaystyle\int_{p_T, p_T^h > p_T^{\mathrm{cut}}} dp_T p_T \, dp_T^h p_T^h \, \frac{d\sigma(pp \to hG^* X)}{dY dy_h d^2 p_T d^2 p_T^h}}{\displaystyle\int_{p_T > p_T^{\mathrm{cut}}} dp_T p_T \, \frac{d\sigma(pp \to G^* X)}{dY d^2 p_T}}}$$

  where p_T^{cut} [1] is the lower cut-off on transverse momenta of dilepton G^* and hadron h and $\Delta\phi$ is the angle between them.

- To describe interactions of the incoming quark with the target color field we employ GBW model for unintegrated gluon distribution function

  $F(x_g, k_T^g) = [\pi Q_s^2(x_g)]^{-1} \, exp(-{k_T^g}^2/Q_s^2(x_g)) \, , Q_s^2(x) = Q_0^2 \left(\frac{x_0}{x}\right)^{\lambda}$ [2]

- KKP fragmentation function $D_{h/f}(z_h, \mu_F^2)$ of a quark with a flavor f into a neutral pion $h = \pi^0$ was used [3].

---

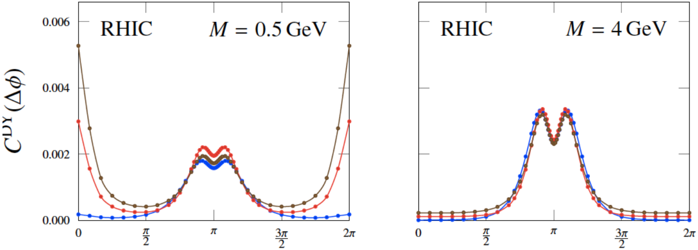
[1] p_T^{cut} =1.5 (3.0) GeV @ RHIC (LHC)

[2] $Q_0^2 = 1$ GeV^2, $x_0 = 3.04 \times 10^{-4}$, $\lambda = 0.288$ and $\sigma_0 = 23.03$ mb were obtained from the fit to the DIS data.

[3] B. A. Kniehl, G. Kramer and B. Potter, Nucl. Phys. B **582**, 514 (2000).

γ^*-π azimuthal correlations in dAu @ RHIC

A. Staśto et al., Nucl. Phys. A 904-905, 837c (2013)



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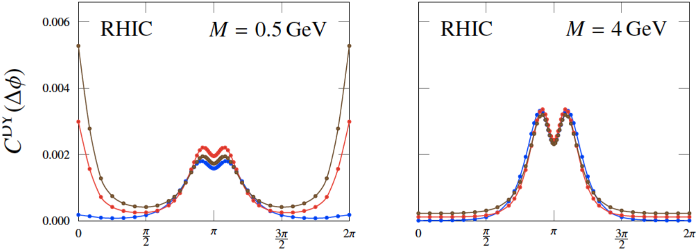
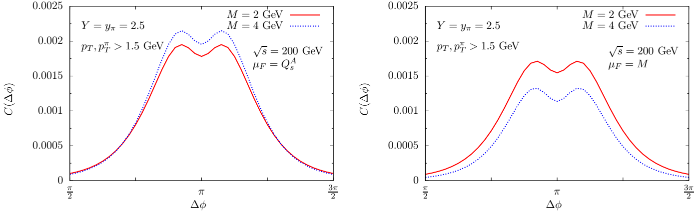


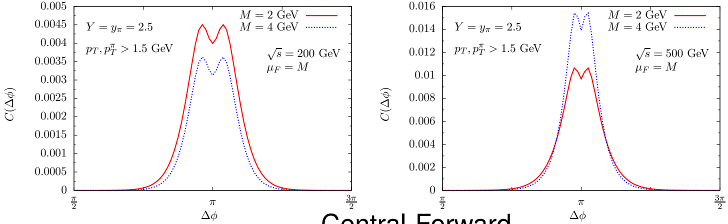
Phys. Rev. D **93**, 034023 (2016)



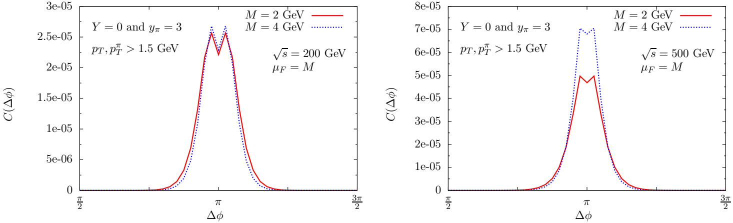
- Similarly to Staśto *et al.* the away-side double-peak structure shows up in dAu.
- Independently of the factorization scale μ_F choice $\Rightarrow$ it is expected also for pp.

γ^*-π azimuthal correlations in pp @ RHIC energies

Forward-Forward



Central-Forward

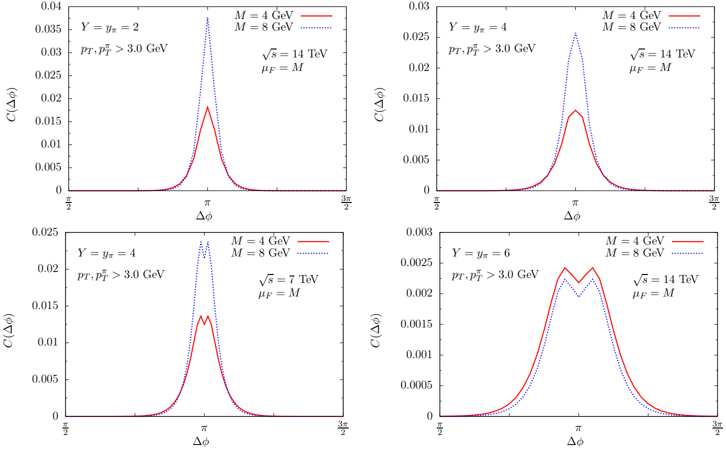


Phys. Rev. D **93**, 034023 (2016)

- Away-side double-peak present also in pp collisions at RHIC.
- Shows up both in Fwd-Fwd and Centr-Fwd correlations $\Rightarrow$ measurable!
- Centr-Fwd correlations are by two orders in magnitude smaller than Fwd-Fwd.

γ^*-π azimuthal correlations in pp @ LHC energies

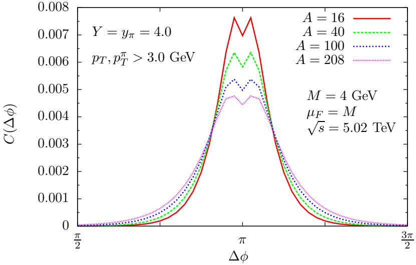
Phys. Rev. D **93**, 034023 (2016)



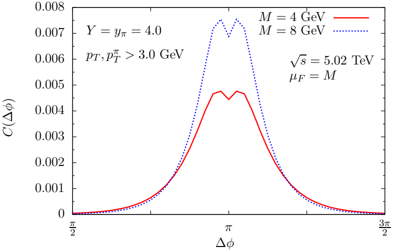
For γ^* and π close to the phase space limit double peak emerges also in *pp* @ LHC.

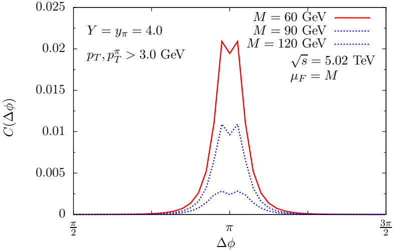
γ^*-π azimuthal correlations in pA @ LHC energies

Phys. Rev. D **93**, 094027 (2016)



Increasing *A* smears the back-to-back pattern and suppresses the away-side peak.





In pPb a double-peak structure shows up also for the large invariant masses.

Dipole Color Singlet Model of Quarkonium Production

Heavy quark pair production in the dipole framework

- Replacing virtual photon with gluon one can try to describe process $G_a + p\ (A) \to q\bar{q}$, ($q = c, b, t$; $a = 1, \ldots, 8$) as a splitting $G \to q\bar{q}$ into dipole in the color background field of the target proton (nucleus).
- In Born approximation dominant contribution to inclusive production, both in open charm and P-wave quarkonia production channels, are:

$$\boxed{\frac{d\sigma(Gp \to q\bar{q}+X)}{d\ln\alpha} = \int d^2\rho\ \left|\Psi_{q\bar{q}}(\alpha,\rho)\right|^2\ \sigma^p_{q\bar{q}}(\alpha\rho, x)}$$

$\Psi_{q\bar{q}}(\alpha,\rho)$ – LC wavefunction giving rate of $G \to q\bar{q}$, can be calculated perturbativelly:

$$\left|\Psi_{q\bar{q}}(\alpha,\rho)\right|^2 = \frac{\alpha_s}{2\pi^2}\left[m_q^2 K_0^2(m_q\rho) + (\alpha^2 + (1-\alpha)^2) K_1^2(m_q\rho)\right]$$

$\sigma^p_{q\bar{q}}$ – dipole cross section for inclusive (singlet + octet) $q\bar{q}$ production (GBW form):

$$\sigma^p_{q\bar{q}} = \sum_{S=1^-,8^\pm} \sigma_3^S = \frac{9}{8}\left[(\sigma_{q\bar{q}}(\alpha\rho) + \sigma_{q\bar{q}}((1-\alpha)\rho)\right] - \frac{1}{8}\sigma_{q\bar{q}}(\rho)$$

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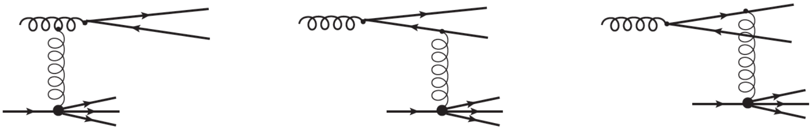

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Dipole Color Singlet Model of $pp \to \{q\bar{q}\}_{1^+} + X$

- In the dipole picture incoming gluon moves along the z-axis.
  $\Rightarrow$ use collinear gluon PDF $xg(x, \mu^2)$ with $k_\perp$-distribution of projectile gluon implicitly integrated out (B. Kopeliovich *et al.*, Nucl. Phys. A **696**, 669 (2001)):

$$\frac{d\sigma^{pp}_{incl}}{dYd\alpha} = x_1 g(x_1, \mu^2) \frac{d\sigma(Gp \to q\bar{q} + X)}{d\alpha}, \; \mu^2 \approx M^2_{q\bar{q}} = \frac{m_q^2 + k_{12}^2}{\alpha(1-\alpha)}$$

  $\Rightarrow$ p_T-distribution of heavy quarkonia is generated by ISR and FSR only.

- LO contribution to C-odd S-wave quarkonium production is due to extra gluon emission off the produced heavy quark $q\bar{q}$ pair state (to produce $\{q\bar{q}\}_{1^+}$ state at least 3 gluons need to be coupled to the quark line).

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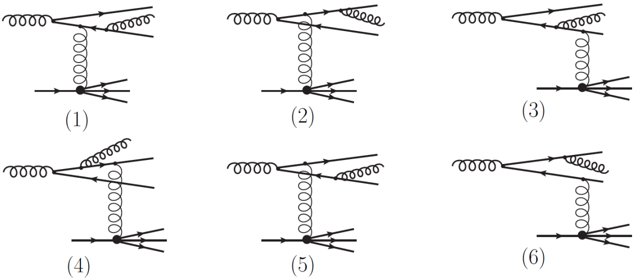
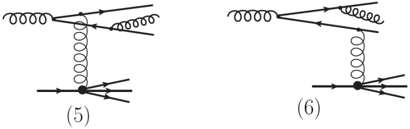


Color-singlet production in association with a gluon

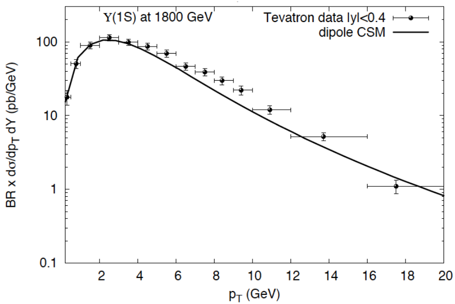
- For S-wave quarkonia (e.g. J/ψ, $\psi(2S)$ and Υ) higher Fock states, e.g. $G + G \to q\bar{q} + G$ need to be included.
- Diagrams (5) and (6) with real gluon emission off a quark different from that coupled to the t-channel gluon are suppressed:

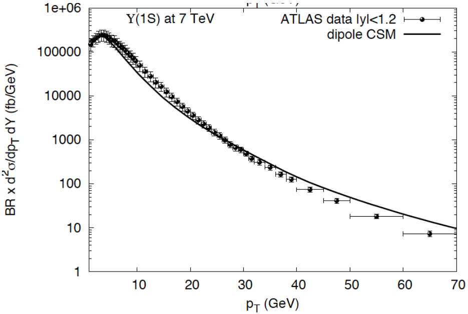


- Momentum transferred by color background field of the target proton to collinearly moving gluon with $k_{1\perp} = 0$ is predominantly longitudinal one (exchanged gluons have typically soft transverse momenta $k_{2\perp} \sim m_g$). $\Rightarrow$ in the perturbative limit, by momentum conservation J/ψ transverse momentum $\vec{p}_T \approx -\vec{k}_3$ is close to that of the radiated gluon $k_3 \gg m_g$.

$\Rightarrow$ Transverse momentum correlation between S-wave quarkonium and (semi-hard) hadron from the fragmentation of the third gluon.

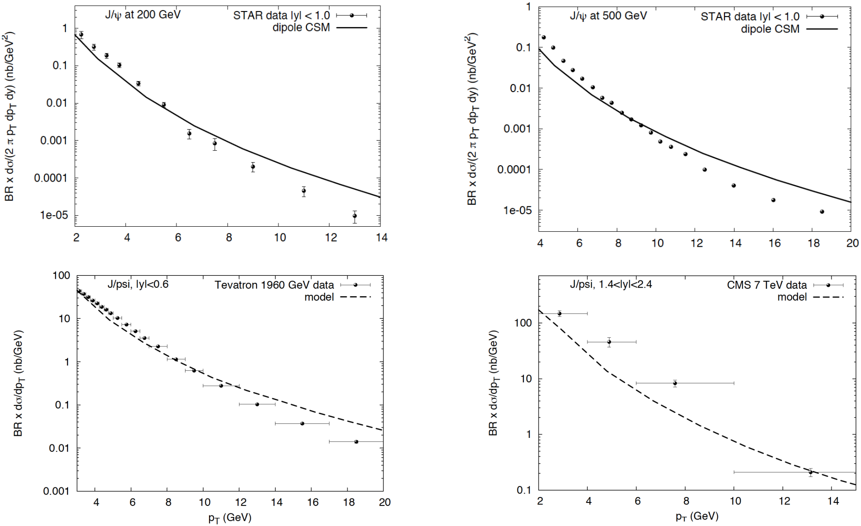
Υ production in pp collisions (preliminary results)





$d\sigma/dp_T dY$ - spectra of $\Upsilon(1s)$ at mid-rapidity, from Tevatron (left) and LHC (right).
CDF: Phys.Rev.Lett. 88 (2002) 161802, ATLAS: arXiv:1211.7255 [hep-ex]

J/ψ production in pp collisions (preliminary results)



Transverse momentum spectra of J/ψ at mid-rapidity, from RHIC (top), Tevatron (bottom left) and LHC (bottom right). CDF: Phys. Rev. Lett. 79, 572 (1997), CMS:arXiv:1111.1557 [hep-ex], STAR: arXiv:1208.2736 [nucl-ex]

Conclusions and Outlook

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- Parameter-free color dipole description of DY production of gauge bosons and quarkonia in *pp*/*pA* was presented. This approach provides universal and robust framework going beyond standard pQCD factorisation.
- DY spectra in *pp*/*pA* are quite sensitive to a different dipole cross section parametrizations.
- γ^*-π azimuthal correlations in *pp* reveal the same away-side double-peak structure observed previously in *p*(*d*)*A* calculations. It is present both in Fwd-Fwd and Centr-Fwd correlations. Width of a double-peak is strongly correlated with the magnitude of the saturation scale Q_s offering thus a possibility for its more direct measurements.
- Description of $\mathrm{d}\sigma/\mathrm{dp_T}$ of J/ψ and Υ within the dipole CSM provides substantial improvement over previous CS NLO calculations. Further test of the model will come from expected quarkonim–(semi-hard) hadron correlation.

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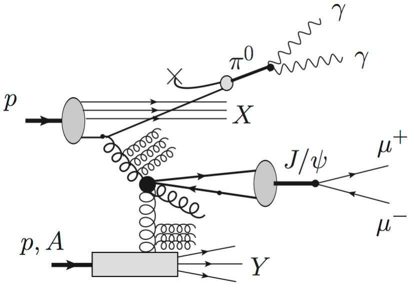
Outlook

- Color dipole approach was used previously to study high-p_T suppression of forward hadrons at RHIC:
  J. Nemchik, *et al.*, Phys. Rev. C 78, 025213(2008)
  J. Nemchik, M. Š., Nucl. Phys. A 830, 611C (2009), PoS ICHEP2010 (2010) 354

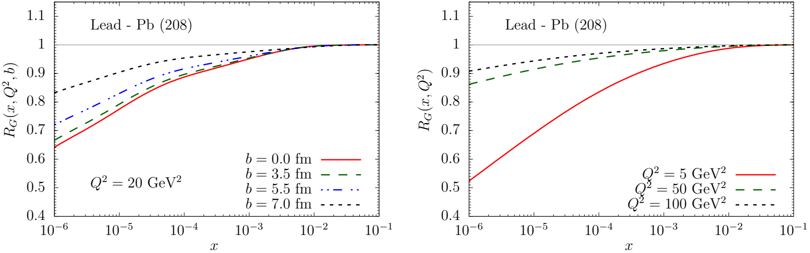


- Joining forward hadron with mid-rapidity quarkonium production
  $\Rightarrow$ forward-central correlations in pp and pA – feasible at RHIC
- New class of measurements will reduce backgrounds and uncertainties in quarkonium production in pp/pA; allows to test h.o. effects in pQCD and disentangle them from e.g. CGC and other multi-particle effects.

Back up slides

Color dipole description of pA collisions

- $\sigma^N_{q\bar{q}}(\rho,x) \to \sigma^A_{q\bar{q}}(\rho,x) = 2\int d^2b\left[1-\exp\left(-\frac{1}{2}T_A(\mathbf{b})\sigma^N_{q\bar{q}}(\rho,x)\right)\right]$
- Gluon shadowing: $\sigma^N_{q\bar{q}}(\rho,x) \to \sigma^N_{q\bar{q}}(\rho,x)\,R_G(x,Q^2,\mathbf{b})$ leads to additional nuclear suppression in production of DY pairs at small x in the target. R_G - ratio of the gluon densities in nuclei and nucleon - was derived in [1]



- Initial-state energy loss suppression of nuclear PDFs at the kinematical limits [2]:

$$q_f(x,Q^2) \to q_f^A(x,Q^2,b) = C_v\,q_f(x,Q^2)\,\frac{e^{-\xi\sigma_{\rm eff}T_A(b)} - e^{-\sigma_{\rm eff}T_A(b)}}{(1-\xi)(1-e^{-\sigma_{\rm eff}T_A(b)})}$$

[1] B.Z. Kopeliovich *et al.* Phys. Rev. **D62**, 054022 (2000); ibid C**65**, 035201 (2002), J. Phys. G**35**, 115010 (2008).
[2] B.Z. Kopeliovich *et al.* Phys. Rev. C**72**, 054066 (2005); Int. J. Mod. Phys. E**23**, 1430006 (2014).